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Review Article

Conflicts in the coastal zone: human impacts on commercially important fish species utilizing coastal habitat

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Coastal ecosystems are ecologically, culturally, and economically important, and hence are under pressure from diverse human activities. We reviewed the literature for existing evidence of effects of human-induced habitat changes on exploited fish utilizing coastal habitats. We focused on fish species of the Northeast Atlantic for which fisheries advice is provided by International Council for the Exploration of the Sea (ICES) and which utilize coastal habitats for at least one life-history stage (LHS). We found that 92% of these species are impacted by human activity in at least one LHS while utilizing coastal habitat and 38% in multiple stages. Anthropogenic pressures most commonly shown to impact these fish species were toxicants and pollutants (75% of species). Eutrophication and anoxia, invasive species, and physical coastal development affected about half of the species (58, 54, and 42% of species, respectively), while indirect fishing impacts affected a minority (17% of species). Moreover, 71% of the ICES advice species that utilize coastal habitats face impacts from more than one pressure, implying cumulative effects. Given that three-fourths of the commercial landings come from fish species utilizing coastal habitats, there is an obvious need for a better understanding of the impacts that human activities cause in these habitats for the development of ecosystem-based fisheries management.

Keywords: anthropogenic pressure, coastal, ecosystem-based management, fisheries, habitat degradation, habitat loss, human activity

Introduction

Coastal habitats (as defined in Seitz *et al.*, 2014) are valuable for numerous fish and invertebrate species, functioning as spawning grounds, juvenile growth areas, foraging areas, and migration corridors (Beck *et al.*, 2001; Elliott and Hemingway, 2002). For example, 44% of the commercially important species for which advice is provided by the International Council for the Exploration of the Sea (ICES) in 2010 in the Northeast Atlantic have been reported to utilize coastal habitats for at least one life-history stage (LHS) for one of the above functions (Seitz *et al.*, 2014).

While coastal and estuarine areas are widely acknowledged to be of high ecological and economic value (Costanza *et al.*, 1997;

de Groot *et al.*, 2012), they are also highly vulnerable and impacted by multiple human activities (Halpern *et al.*, 2007, 2009; Crain *et al.*, 2008; Batista *et al.*, 2014; Vasconcelos *et al.*, 2017). In temperate regions, coastal habitats such as rocky intertidal and subtidal reefs, mudflats, seagrass meadows, kelp forests, and salt marshes are exposed to high levels of anthropogenic pressures (Lotze *et al.*, 2005; Airoldi and Beck, 2007; Halpern *et al.*, 2008).

Diverse activities - whether urban, industrial, agricultural, land reclamation, or direct exploitation of resources in the estuarine and coastal realm - often impose several pressures with cumulative impacts on coastal fish habitats (Vasconcelos *et al.*, 2007). With human populations continuously increasing and aggregating around coastal areas worldwide (Airoldi and Beck, 2007; Kummu *et al.*, 2016), space for human settlement and activities is often gained through land reclamation, i.e. implying the loss and fragmentation of shallow-water aquatic coastal habitats. In addition, loss, modification, and fragmentation of aquatic coastal habitats is also caused by changes to hydrological regimes, novel artificial coastal defence structures, substrate extraction (e.g. mining or dredging for maintenance of navigation canals), and disposal (e.g. coastal nourishment) (Borja *et al.*, 2010; Peterson *et al.*, 2014). In terms of physical perturbations, destructive fishing methods such as bottom trawling also disrupt important fish habitats (Hiddink *et al.*, 2006). Simultaneously, degradation of coastal fish habitats can also be brought about through eutrophication and subsequent macroalgal blooms (Rabalais, 2015; Le Luherne *et al.*, 2016) or anoxic events (Cloern, 2001) derived from nutrient input associated with urban and agricultural activities. Other terrestrial and coastal activities (e.g. industry and mining) introduce a variety of xenobiotics, which impact regular physiological processes of fish and other organisms across different trophic levels (Davis, 1999). Concurrently, the transport of people, goods, and animals often lead to the introduction of non-native species and subsequent ecological disruption (Molnar *et al.*, 2008).

Since the onset of industrialization, human activities in coastal seas and estuaries have caused successive changes in habitat quantity and quality for many key fish species (Lotze *et al.*, 2006; Vasconcelos *et al.*, 2007). Resulting ecological effects can be extended to the provisioning of ecosystem services, e.g. effects on the availability of fish for viable commercial and recreational fisheries or of food and habitat for protected species (Holmlund and Hammer, 1999; Lotze *et al.*, 2006; Worm *et al.*, 2006).

In the Northeast Atlantic, coastal ecosystems are bordered by dense human populations and thus are severely affected by cumulative anthropogenic pressures (Airoldi and Beck, 2007; Halpern *et al.*, 2009). In this region, a wide acknowledgement of the overexploitation of many commercially important species has led to the coordination of fisheries management actions at national and European levels (Lagares and Ordaz, 2014). Yet, the effects of other human-driven pressures on fish in coastal habitats of this region have been poorly collectively evaluated or insufficiently taken into consideration in species conservation or marine resource management plans (Kempf, 2010; Jennings and Rice, 2011). These effects must be estimated, according to the European Marine Strategy Framework Directive (MSFD; 2008/56/EC), so that measures can be taken to achieve "good environmental status", by 2020.

In this study, we aim to make a critical assessment of the impacts and perturbations in coastal habitats on different life-history stages of commercially important fish. We focus on fish populations in the Northeast Atlantic for which fisheries advice is provided by ICES (henceforth referred to as ICES advice species). To achieve our aim, we build upon the seminal paper by Seitz *et al.* (2014) by reviewing existing literature to find evidence of impacts (negative or positive) on commercially important fish species from coastal habitat changes caused by human activities. We discuss our results in relation to ongoing improvements in quantifying human impacts on coastal fish. We then make suggestions for future research and propose potential avenues for incorporating fish habitat considerations into ecosystem-based fisheries management.

Methods

We searched existing primary literature to assess the extent to which ICES advice fish species are impacted by human activities in coastal habitats. The aim here was to find evidence of impacts (i) across species, (ii) by coastal LHS (i.e. juvenile, feeding, spawning, migration; Figure 1), and (iii) across different sources of anthropogenic pressures. Species investigated were those for which ICES provides advice. The coastal use of different life-history stages was taken from Seitz *et al.* (2014) and updated using their methodology (see Supplementary Material). To differentiate between anthropogenic pressures, we placed the most commonly occurring pressures into five categories (Table 1). The "Physical Coastal Development" category deals with both physical changes to the aquatic environment (e.g. human-induced changes in surface sediment properties) and loss of area (e.g. marina construction or land reclamation). The "Eutrophication and Anoxia" category deals with changes in nutrient and oxygen concentrations. The "Toxicants and Pollutants" category deals with toxic substances and xenobiotics present or entering the coastal habitat as a result of human activity. The "Invasive Species" category refers to introduced, non-native species that become abundant and alter ecosystem structures and functions. The "Indirect Fishing Impacts" category excludes direct fishing mortality but deals with effects such as physical disturbance of the seabed, destruction of reefs, or changes in community structure through the removal of key species.

We compiled relevant scientific literature linking habitat degradation to coastal life-history stages. A database search initially utilized Google Scholar on 21 July 2015 combining species' name (both binomial and common) with keywords relevant to different categories of habitat degradation (Table 1). This list was updated, and the collection increased using searches of the same format later in 2015 and from authors' own literature databases. We evaluated the results of this search to compile a three-dimensional inventory of evidence of impacts for each species, each LHS, and each pressure ($24 \times 4 \times 5 = 480$, respectively). Once evidence of impact was found for a given inventory position, the search moved on to the next position. The amount of research found and the magnitude of impact effects were not quantified; hence, the result was a binary table (evidence or no evidence). From this inventory of evidence, we calculated the relative proportions of impacted species and life-history stages and of the respective category of anthropogenic pressure involved.

Results

Evidence of human activities impacting ICES advice species in coastal habitats was collated by category of anthropogenic pressure and LHS (Table 2). Considering all 5 impact categories, 4 life-history stages, and 24 species utilizing coastal habitat, a total of 58 occurrences of anthropogenic impact were found (Table 2). Of these 24 fish species, 92% (22) were impacted by at least one category of human activity in one or more life-history stages in coastal habitats. The category of impacts most commonly linked to fish in coastal habitats was "Toxicants and Pollutants", with 75% (18/24) of species having evidence of being impacted in at least one LHS (Figure 2). "Eutrophication and Anoxia" and "Invasive Species" both affected over half of species with coastal habitat use with 58% (14/24) and 54% (13/24), respectively. "Physical Coastal Development" impacted 42% (11/24) of species, while least commonly documented was the "Indirect Fishing Impacts" category where 17% (4/24) of ICES advice species utilizing the coast were shown to be linked to these types of impacts. Moreover, 71% (17/24) of species face impacts from more than one pressure (Table 2).

When considering individual life-history stages (Table 3), 54% (13/24) of fish species utilizing coastal habitats were impacted in only one LHS, while 38% (9/24) had evidence of two or more life-history stages being impacted. If we consider only those species utilizing coastal habitats for two or more life-history stages (15/24), then 60% (9/15) of these had evidence of being impacted. For two species, Norway pout (*Trisopterus esmarkii*) and sandeel (*Ammodytes* spp.), no evidence of anthropogenic impacts was found in the literature.

We found that 69% (34/49, i.e. total no. crosses/total no. shaded cells in Table 3) of life-history stages utilizing coastal habitats have documented evidence of being impacted by human activity. Within each LHS utilizing coastal habitat (Figure 3), the juvenile LHS had the most evidence of being impacted both by proportion (78%) and absolute number (14/18; Table 3). The feeding LHS was impacted at a slightly lower rate of 69% (11/16), while two-thirds (6/9) of species utilizing coastal habitats for spawning had evidence of human impacts. The migration LHS had the fewest species with evidence of impacts from human activity, where 50% (3/6) of the occasions of coastal utilization were impacted.

Discussion

Coastal habitats experience a large variety and extent of anthropogenic pressures (Lotze *et al.*, 2006; Airoldi and Beck, 2007; Halpern *et al.*, 2008; Vasconcelos *et al.*, 2017); hence, the many fish species utilizing these habitats across different parts of their LHS may also be impacted by human activities. Based on the occurrence of reported impacts, this study highlights the current evidence of such impacts across the Northeast Atlantic.

A major conclusion of this review is that there is a large body of evidence linking a variety of human activities and habitat degradation to impacts on commercially important fishes utilizing coastal habitats. In fact, 92% of ICES fish species utilizing coastal habitats were found to be impacted by at least one pressure in these habitats. Species with certain life-history stages exhibiting a strong dependence on specific habitat types are especially at risk of habitat loss and degradation, which is usually the case for early life-history stages (i.e. juvenile LHS in the present study; Mumby *et al.*, 2004; Seitz *et al.*, 2014; Sundblad *et al.*, 2014).

While our assessment targets only the presence or absence of impacts for each species and LHS, some commonalities are to be mentioned concerning the effects and mechanisms of the different impact categories on fish utilizing coastal habitats. Eutrophication, for example, was found to impair spawning and recruitment via periodic increases in primary production from certain algal species (Isaksson *et al.*, 1994; Carl *et al.*, 2008). Although mild eutrophication was also found to increase the productivity of some systems (Parmanne *et al.*, 1994; Österblom *et al.*, 2007),

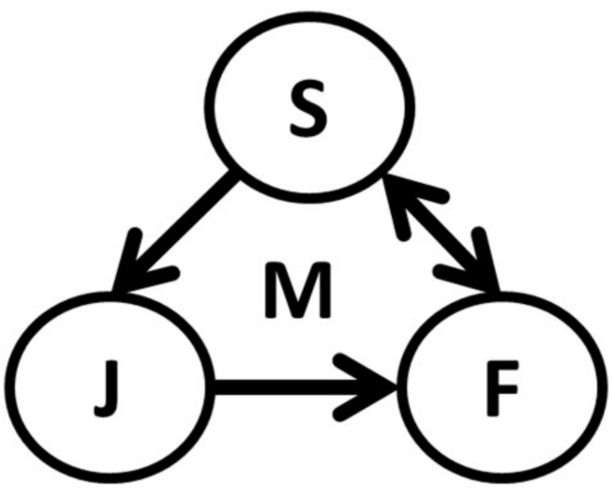

Figure 1. Conceptual diagram of common life-history stages of fish in coastal habitats: S = mature adults during spawning, J = immature juveniles, and F = feeding adults not in spawning. Arrows represent migrations (M).

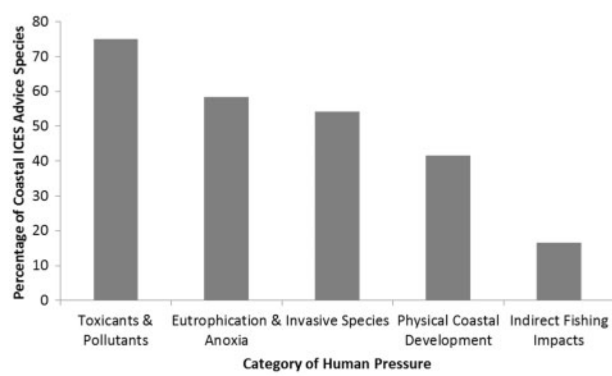

Figure 2. Percentage (by number) of ICES advice species that utilize the coastal zone and have evidence of being impacted by anthropogenic pressures separated by pressure category.

Table 1. Keywords used to define habitat degradation in review of human impacts on fish using coastal habitats in different life-history stages.

Anthropogenic pressure	Relevant keywords used in search
Toxicants and Pollutants	"xenobiotics" or "toxic* or "sewage" or "contaminant" or "pollution"
Eutrophication and Anoxia	"eutrophication" or "hypoxia"
Invasive Species	"invasi*" or "outbreak" or "proliferation"
Physical Coastal Development	"land reclamation" or "sediment" or "habitat loss" or "extraction" or "depth change"
Indirect Fishing Impacts	"fishing" or "trawling" or "dredging"

Table 2. Anthropogenic pressures impacting commercially important fish species in coastal habitats for which ICES provides advice.

		Anthropogenic pressure					
Species	**Common name**	**Toxicants and Pollutants**	**Eutrophication and Anoxia**	**Invasive Species**	**Physical Coastal Development**	**Indirect Fishing Impacts**	**References**
Engraulis encrasicolus	Anchovy		S	J F			Tsikhon-Lykanina and Reznitchenko (1991), Kideys (1994), Niermann *et al.* (1994), Shiganova *et al.* (2001), Drake *et al.* (2007), Oguz *et al.* (2008), Ruiz *et al.* (2009), Ekau *et al.* (2010)
Cetorhinus maximus	Basking shark	F					Fossi *et al.* (2014)
Scophthalmus rhombus	Brill			J			Kostecki et *al*., (2011)
Mallotus villosus	Capelin	S					Frantzen *et al.* (2012)
Gadus morhua	Cod	F	J F	F	F	J	Isaksson *et al.* (1994), Lindholm *et al.* (1999), Hall-Spencer *et al.* (2003), Johansen *et al.* (2006, 2011), Österblom *et al.* (2007), Patel *et al.* (2007), Teschner *et al.* (2010), Thurstan *et al.* (2010), Malovic *et al.* (2010), Bratberg *et al.* (2013), Reubens *et al.* (2013), Johannessen (2014)
Limanda limanda	Dab	F	J			J	Berghahn *et al.* (1992), Houlihan *et al.* (1994), Petersen and Pihl (1995), Power *et al.* (2000)
Anguilla anguilla	Eel	M	M		M		Feunteun (2002), Palstra *et al.* (2006), Maes *et al.* (2007)
Dicentrarchus labrax	European sea bass	J			J		Laffaille *et al.* (2000), Reynolds *et al.* (2003), Kerambrun *et al.* (2012b)
Platichthys flesus	Flounder	J	J	J			Carl *et al.* (2008), Amara *et al.* (2009), Kostecki *et al.* (2011), Jokinen *et al.* (2016)
Clupea harengus	Herring	S	S	S	S		Johnston and Wildish (1981), Winters *et al.* (1986), Aneer (1987), Costello and Gamble (1992), Kornilovs (1993), Lappalainen and Pesonen (2000), Gorokhova *et al.* (2004, 2005), McIntosh *et al.* (2010), Frantzen *et al.* (2015)
Scomber scombrus	Mackerel	S		J			Longwell *et al.* (1992), Öztürk (2006)
Trisopterus esmarkii	Norway pout						
Pleuronectes platessa	Plaice	J	F J	J	J	J	Petersen and Pihl (1995), Secombes *et al.* (1995), Pihl *et al.* (2005), van de Wolfshaar *et al.* (2011)
Pollachius pollachius	Pollack		J				Johannessen (2014)
Pollachius virens	Saithe	J		J	J	J	Bordehore *et al.* (2003), Kamenos *et al.* (2004), Olsen *et al.* (2010), Falk-Petersen *et al.* (2011), Støttrup *et al.* (2014)
Salmo salar	Salmon		M		M		Alabaster *et al.* (1991), Tentelier and Piou (2011), Martignac *et al.* (2013)
Ammodytes marinus	Sandeel						

Continued

Table 2. continued

		Anthropogenic pressure					
Species	**Common name**	**Toxicants and Pollutants**	**Eutrophication and Anoxia**	**Invasive Species**	**Physical Coastal Development**	**Indirect Fishing Impacts**	**References**
Sardina pilchardus	Sardine	F	F				Canli and Atli (2003), Goren and Galil (2005)
Salmo trutta	Sea trout	F	M	F M			Olsson *et al.* (2001), Meland *et al.* (2010), Ilarri *et al.* (2014), Taranger *et al.* (2015)
Solea solea	Sole	J F	J	J	J		Via *et al.* (1998), Lefrançois and Claireaux (2003), Le Pape *et al.* (2004), Gilliers *et al.* (2006), Amara *et al.* (2007), Davoodi and Claireaux (2007), Jenkinson *et al.* (2007), Rochette *et al.* (2010), Kostecki *et al.* (2011), Jebali *et al.* (2013)
Sprattus sprattus	Sprat	S	J	J F S	J		Parmanne *et al.* (1994), Cameron and Von Westernhagen (1997), Shiganova and Bulgakova (2000), Peters *et al.* (2001), Österblom *et al.* (2007)
Mullus surmuletus	Striped red mullet	F		F			Levi and Francour (2004), Bianchi *et al.* (2014), Scopelliti *et al.* (2015)
Scophtalmus maximus	Turbot	J					Kerambrun *et al.* (2012a, 2012b)
Merlangius merlangus	Whiting	S	F		J		Westernhagen *et al.* (1989), Shiganova and Bulgakova (2000), Turnpenny and Taylor (2000), Ogut and Palm (2005), Pihl *et al.* (2006)
Percentage of species		75%	58%	54%	42%	17%	

Evidence of impacts at different life-history stages is indicated by J (juvenile), F (feeding), S (spawning), and M (migration).

higher nutrient loads may negatively impact fish populations by decreasing the cover of canopy forming vegetation (Cloern, 2001) and increasing the frequency of anoxic events (Rabalais, 2015), in turn causing increases in the mortality of early life-history stages and reducing growth rates in fish (Kornilovs, 1993; Petersen and Pihl, 1995; Maes *et al.*, 2007; Teschner *et al.*, 2010). In addition to the widely known direct effects of fishing on fish species, this study found that fishing often indirectly impacted fish through the destruction of biogenic structures which provide shelter (Hall-Spencer *et al.*, 2003; Kamenos *et al.*, 2004). Furthermore, trawling also causes physical damage to abiogenic bottom habitats causing changes in benthic invertebrate communities (Sciberras and Hiddink, 2014; van Denderen *et al.*, 2014; Rijnsdorp *et al.*, 2016), which can be expected to affect fish populations as they are important prey for fish (Henriques *et al.*, 2014). Invasive species were mostly noted to either directly exploit or compete for food with resident species (Öztürk, 2006; Oguz *et al.*, 2008) or otherwise alter the structure of the habitat (Pihl *et al.*, 2005). Physical development was reported to lead to reduced productivity via dams altering terrestrial water discharge regimes in nursery areas (Drake *et al.*, 2002) and the direct removal of habitat via dredging, diking, and harbour extensions (Rochette *et al.*, 2010). However, other physical developments may lead to habitat creation due to artificial hard substrates providing shelter and feeding opportunities (Reubens *et al.*, 2013). Impacts from xenobiotics ranged from egg mortality through decreased growth rates to reduced migration success (Houlihan *et al.*, 1994; Feunteun, 2002; Kerambrun *et al.*, 2012a), all of which lead to lowered fish survival (Gilliers *et al.*, 2006; Le Pape *et al.*, 2007) and density (Courrat *et al.*, 2009; Delpech *et al.*, 2010).

In reality, the impacts that fish experience in coastal habitats are not acting in isolation, but interact to form a complex combination of cumulative impacts (Lotze *et al.*, 2006; Halpern *et al.*, 2007; Vasconcelos *et al.*, 2007). In coastal habitats, fish can face cumulative impacts both in terms of different anthropogenic pressures and in terms of exposure during more than one LHS. In this study, 71% of species had evidence of exposure to multiple impact categories. A good example of this is the plaice (*Pleuronectes platessa*), where the juvenile LHS had a reported impact from all five impact categories examined in this study. Similarly, sprat (*Sprattus sprattus*) juveniles are faced with impacts from three impact categories: “Eutrophication and Anoxia”, “Invasive Species”, and “Physical Coastal Development”. Furthermore, there is evidence of human impacts affecting sprat across three of the four life-history stages illustrating additional cumulative impacts over time. Similar cumulative impacts acting across different life-history stages are faced by

Table 3. ICES advice species showing coastal habitat use.

		Life history stage			
Common name	**Binomial classification**	**Juvenile**	**Feeding**	**Spawning**	**Migration**
Anchovy	*Engraulis encrasicolus*	X	X	X	
Basking shark	*Cetorhinus maximus*		X		
Brill	*Scophthalmus rhombus*	X			
Capelin	*Mallotus villosus*			X	
Cod	*Gadus morhua*	X	X		
Dab	*Limanda limanda*	X	X		
Eel	*Anguilla anguilla*				X
European sea bass	*Dicentrarchus labrax*	X			
Flounder	*Platichthys flesus*	X			
Herring	*Clupea harengus*			X	
Mackerel	*Scomber scombrus*	X		X	
Norway pout	*Trisopterus esmarkii*				
Plaice	*Pleuronectes platessa*	X	X		
Pollock	*Pollachius pollachius*	X			
Saithe	*Pollachius virens*	X			
Atlantic salmon	*Salmo salar*				X
Sandeel	*Hyperoplus spp./Ammodytes spp.*				
Sardine	*Sardina pilchardus*		X		
Sea trout	*Salmo trutta*		X		X
Sole	*Solea solea*	X	X		
Sprat	*Sprattus sprattus*	X	X	X	
Striped red mullet	*Mullus surmuletus*		X		
Turbot	*Scophthalmus maximus*	X			
Whiting	*Merlangus merlangus*	X	X	X	
Percentage of species with evidence of impact for life-history stages that utilize coastal habitat		**78%**	**69%**	**67%**	**50%**

Updated from Seitz *et al.*, 2014 (see Supplementary Material) in different life-history stages (shaded cells) and those life-history stages found (this study) to be impacted upon by human activities (marked by X)

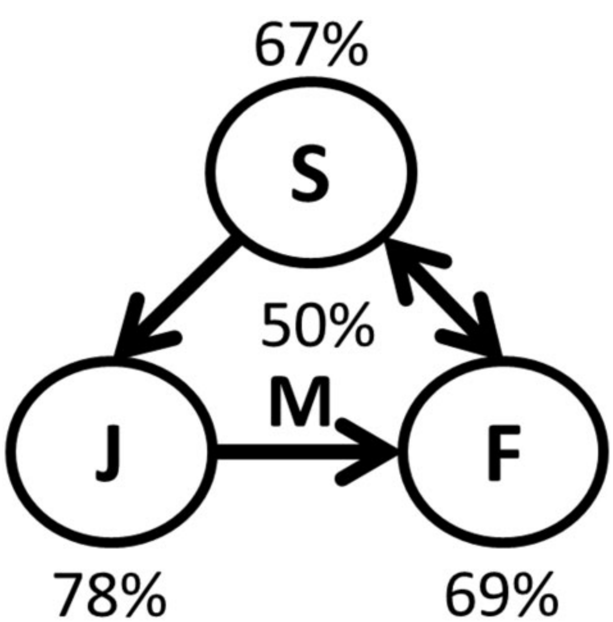

Figure 3. Conceptual diagram of common life-history stages of fish in coastal habitats displaying the percentage of impacted species at each LHS (S = mature adults during spawning, J = immature juveniles, and F = feeding adults not in spawning). Arrows represent migrations (M).

38% of the species, without considering human impacts experienced in offshore habitats. Impacts imposed at a given LHS may continue to have an effect throughout the remainder of the life cycle (Schmidt *et al.*, 2012). For example, exposure to xenobiotics at the juvenile LHS, affecting juvenile growth and survival (Gilliers *et al.*, 2006), also impacts adult fitness (Jonsson and Jonsson, 2014).

The cumulative impacts from these multiple stressors can be additive, synergistic, or antagonistic (for definitions, see Crain *et al.*, 2008; Piggott *et al.*, 2015). In marine ecosystems, cumulative impacts are often synergistic (Crain *et al.*, 2008). In coastal marine systems, more than half of combined impacts are derived from non-additive interactions, meaning simple additive approaches are often insufficient to adequately describe or predict impacts (Teichert *et al.*, 2016). A simple illustration of synergistic cumulative impacts is the multiplicative effect of habitat loss and the simultaneous degradation of habitat quality in residual habitats (Archambault *et al.*, 2015). So-called positively synergistic stressors, where multiple pressures amplify the stress on species, will have the largest impact, potentially altering entire assemblages (Tomczak *et al.*, 2013). The identification and mitigation of such combinations of anthropogenic pressures and effects along successive life-history stages will also have the largest scope for restoration benefits (Piggott *et al.*, 2015). The results of the current work provide some guidance with regard to species, different life-history stages, and the types of pressures to be considered in cumulative impact studies.

Knowledge of these impacts and their interrelated effects on fish populations needs to be quantified to be useful in management. An integrated population model (IPM) that quantifies key demographic rates across different life-history stages has proven successful in describing population changes and trends related to environmental drivers (Deegan, 1990; Fodrie *et al.*, 2009). Like all modelling approaches, IPMs can only create good approximations of reality when informed with accurate parameters, of which IPMs require many (Koons *et al.*, 2017). Because of the complexity involved in linking many submodels together, many constructions have excluded important drivers (Klanjšček and Legović, 2007), used explicit assumptions (Levin and Stunz, 2005), or failed to consider the assumptions of underlying models (Anderson, 2005), thus reducing the applicability to scenario-based predictions. This is not to say that such endeavours are not warranted; to the contrary, they can act as informed thought experiments in probing ecological questions (Levin and Stunz, 2005). However, such approaches should be iterative (Rochette *et al.*, 2013; Archambault *et al.*, 2015, 2016) and considered with an appropriate level of criticism until research in the system they aim to describe matures and provides ample and accurate parameters to inform the model (Meynecke and Richards, 2014; Archambault *et al.*, 2016). In the short term, approaches that reduce the number of parameters in a model can provide better predictions of population changes (Ruiz *et al.*, 2009). However, in complex systems with multiple pressures, the exclusion of certain drivers will neglect both their direct impact and any cumulative impacts on the population. Studies that include more and more accurately parameterized drivers in constructing IPMs can provide better insight into how cumulative impacts affect populations and hence better inform management of these stocks and resources (van de Wolfshaar *et al.*, 2011).

Taking this approach a step further involves applying IPMs from mature research areas to spatially explicit contexts (e.g. Stelzenmüller *et al.*, 2011; van de Wolfshaar *et al.*, 2011; Meynecke and Richards, 2014; Archambault *et al.*, 2015; Rahikainen *et al.*, 2017). To properly parameterize and to make these approaches more accurate and ubiquitous, research focus and investment should be made in empirical studies to link drivers to population demographic rates at specific life-history stages.

With knowledge of the population-level effects of cumulative anthropogenic pressures, trade-offs of impacts under alternative scenarios of use can be investigated. Information on the sensitivity of different habitats and fish populations across their entire life history to individual pressures may then be represented by impact scores and mapped, while cumulative effects are subsequently considered (Halpern *et al.*, 2008; Foden *et al.*, 2011; Andersen *et al.*, 2015). Such methods of estimating cumulative impacts on ecosystems are currently being developed for marine management and spatial planning purposes (Goodsir *et al.*, 2015; Knights *et al.*, 2015). Providing authorities with fish habitat maps together with quantitative information on the effects of human pressures would be an important step towards securing long-term sustainability of these coastal habitats and the ecosystem services they provide. While the development of these mapping methods continues, there is a parallel need to develop ways to integrate this new knowledge with fisheries management and maritime spatial planning (EU Directive MSP 2014/89/EU).

Our study indicates a high variety of how and where, within a species' life history, anthropogenic pressures in coastal habitats may impact commercially important fish. It also discusses the development of methods to investigate population effects of such impacts and highlights knowledge gaps in this area of research. Considering that the majority of commercial landings come from fish utilizing coastal habitats (ca. 75%) (Champbers, 1991—cited in Fodrie and Mendoza, 2006; Seitz *et al.*, 2014; Supplementary Material), it is of great importance that the impacts of human activities in coastal areas are understood and accounted for in the context of ecosystem-based fisheries management.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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References

Airoldi, L., and Beck, M. W. 2007. Loss, status and trends for coastal marine habitats of Europe. Oceanography and Marine Biology: An Annual Review 45: 345–405.

Alabaster, J. S., Gough, P. J., and Brooker, W. J. 1991. The environmental requirements of Atlantic salmon, *Salmo salar* L., during their passage through the Thames Estuary, 1982-1989. Journal of Fish Biology 38: 741–762.

Amara, R., Meziane, T., Gilliers, C., Hermel, G., and Laffargue, P. 2007. Growth and condition indices in juvenile sole *Solea solea* measured to assess the quality of essential fish habitat. Marine Ecology Progress Series 351: 201–208.

Amara, R., Selleslagh, J., Billon, G., and Minier, C. 2009. Growth and condition of 0-group European flounder, *Platichthys flesus* as indicator of estuarine habitat quality. Hydrobiologia 627: 87–98.

Andersen, J. H., Halpern, B. S., Korpinen, S., Murray, C., and Reker, J. 2015. Baltic Sea biodiversity status vs. cumulative human pressures. Estuarine, Coastal and Shelf Science 161: 88–92.

Anderson, T. R. 2005. Plankton functional type modelling: running before we can walk? Journal of Plankton Research 27: 1073–1081.

Aneer, G. 1987. High natural mortality of Baltic herring (*Clupea harengus*) eggs caused by algal exudates? Marine Biology 94: 163–169.

Archambault, B., Le Pape, O., Baulier, L., Vermard, Y., Véron, M., and Rivot, E. 2016. Adult-mediated connectivity affects inferences on population dynamics and stock assessment of nursery-dependent fish populations. Fisheries Research 181: 198–213.

Archambault, B., Rivot, E., Savina, M., and Le Pape, O. 2015. Using a spatially structured life cycle model to assess the influence of multiple stressors on an exploited coastal-nursery-dependent population. Estuarine, Coastal and Shelf Science: 1–10. http://dx.doi.org/10.1016/j.ecss.2015.12.009.

Batista, M. I., Henriques, S., Pais, M. P., and Cabral, H. N. 2014. Assessment of cumulative human pressures on a coastal area: integrating information for MPA planning and management. Ocean and Coastal Management 102: 248–257.

Beck, M. W., Heck, K. L., Able, K. W., Childers, D. L., Eggleston, D. B., Gillanders, B. M., and Halpern, B. S. 2001. The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates. BioScience 51: 633.

Berghahn, R., Waltemath, M., and Rijnsdorp, A. D. 1992. Mortality of fish from the by-catch of shrimp vessels in the North Sea. Journal of Applied Ichthyology 8: 293–306.

Bianchi, C. N., Corsini-Foka, M., Morri, C., and Zenetos, A. 2014. Thirty years after: dramatic change in the coastal marine ecosystems of Kos Island (Greece), 1981-2013. Mediterranean Marine Science 15: 482–497.

Bordehore, C., Ramos-Espla, A. A., and Riosmena-Rodriguez, R. 2003. Comparative study of two maerl beds with different otter trawling history, southeast Iberian Peninsula. Aquatic Conservation: Marine and Freshwater Ecosystems 13: S43–S54.

Borja, Á., Dauer, D. M., Elliott, M., and Simenstad, C. A. 2010. Medium and long-term recovery of estuarine and coastal ecosystems: patterns, rates and restoration effectiveness. Estuaries and Coasts 33: 1249–1260.

Bratberg, M., Olsvik, P. A., Edvardsen, R. B., Brekken, H. K., Vadla, R., and Meier, S. 2013. Effects of oil pollution and persistent organic pollutants (POPs) on glycerophospholipids in liver and brain of male Atlantic cod (*Gadus morhua*). Chemosphere 90: 2157–2171.

Cameron, P., and Von Westernhagen, H. 1997. Malformation rates in embryos of North Sea fishes in 1991 and 1992. Marine Pollution Bulletin 34: 129–134.

Canli, M., and Atli, G. 2003. The relationships between heavy metal (Cd, Cr, Cu, Fe, Pb, Zn) levels and the size of six Mediterranean fish species. Environmental Pollution 121: 129–136.

Carl, J. D., Sparrevohn, C. R., Nicolajsen, H., and Stttrup, J. G. 2008. Substratum selection by juvenile flounder *Platichthys flesus* (L.): effect of ephemeral filamentous macroalgae. Journal of Fish Biology 72: 2570–2578.

Cloern, J. E. 2001. Our evolving conceptual model of the coastal eutrophication problem. Marine Ecology Progress Series 210: 223–253.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K. et al. 1997. The value of the world's ecosystem services and natural capital. Nature 387: 253–260.

Costello, M. J., and Gamble, J. C. 1992. Effects of sewage sludge on marine fish embryos and larvae. Marine Environmental Research 33: 49–74.

Courrat, A., Lobry, J., Nicolas, D., Laffargue, P., Amara, R., Lepage, M., Girardin, M. et al. 2009. Anthropogenic disturbance on nursery function of estuarine areas for marine species. Estuarine, Coastal and Shelf Science 81: 179–190.

Crain, C. M., Kroeker, K., and Halpern, B. S. 2008. Interactive and cumulative effects of multiple human stressors in marine systems. Ecology Letters 11: 1304–1315.

Davis, J. F. 1999. Fate of environmental pollutants. Water Environment Research 71: 1070–1078.

Davoodi, F., and Claireaux, G. 2007. Effects of exposure to petroleum hydrocarbons upon the metabolism of the common sole *Solea solea*. Marine Pollution Bulletin 54: 928–934.

de Groot, R., Brander, L., van der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christie, M. et al. 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosystem Services 1: 50–61.

Deegan, L. A. 1990. Effects of estuarine environmental conditions on population dynamics of young-of-the-year Gulf menhaden. Marine Ecology Progress Series 68: 195–205.

Delpech, C., Courrat, A., Pasquaud, S., Lobry, J., Le Pape, O., Nicolas, D., Boët, P., Girardin, M. et al. 2010. Development of a fish-based index to assess the ecological quality of transitional waters: the case of French estuaries. Marine Pollution Bulletin 60: 908–918.

Drake, P., Arias, A. M., Baldó, F., Cuesta, J. A., Rodríguez, A., Silva-Garcia, A., and Sobrino, I. 2002. Spatial and temporal variation of the nekton and hyperbenthos from a temperate European estuary with regulated freshwater inflow. Estuaries 25: 451–468.

Drake, P., Borlán, A., González-Ortegón, E., Baldó, F., Vilas, C., and Fernández-Delgado, C. 2007. Spatio-temporal distribution of early life stages of the European anchovy *Engraulis encrasicolus* L. within a European temperate estuary with regulated freshwater inflow: effects of environmental variables. Journal of Fish Biology 70: 1689–1709.

Ekau, W., Auel, H., Pörtner, H.-O., and Gilbert, D. 2010. Impacts of hypoxia on the structure and processes in pelagic communities (zooplankton, macro-invertebrates and fish). Biogeosciences 7: 1669–1699.

Elliott, M., and Hemingway, K. 2002. Fishes in estuaries. *In* Fishes in Estuaries, pp. i–xx. Ed. by M. Elliott, and K. Hemingway. Blackwell Science, Oxford.

Falk-Petersen, J., Renaud, P., and Anisimova, N. 2011. Establishment and ecosystem effects of the alien invasive red king crab (*Paralithodes camtschaticus*) in the Barents Sea—a review. ICES Journal of Marine Science 68: 479–488.

Feunteun, E. 2002. Management and restoration of European eel population (*Anguilla anguilla*): an impossible bargain. Ecological Engineering 18: 575–591.

Foden, J., Rogers, S. I., and Jones, A. P. 2011. Human pressures on UK seabed habitats: a cumulative impact assessment. Marine Ecology Progress Series 428: 33–47.

Fodrie, F. J., and Mendoza, G. 2006. Availability, usage and expected contribution of potential nursery habitats for the California halibut. Estuarine, Coastal and Shelf Science 68: 149–164.

Fodrie, F. J., Levin, L. A., and Lucas, A. 2009. Use of population fitness to evaluate the nursery function of juvenile habitats. Marine Ecology Progress Series 385: 39–49.

Fossi, M. C., Coppola, D., Baini, M., Giannetti, M., Guerranti, C., Marsili, L., Panti, C. et al. 2014. Large filter feeding marine organisms as indicators of microplastic in the pelagic environment: the case studies of the Mediterranean basking shark (*Cetorhinus maximus*) and fin whale (*Balaenoptera physalus*). Marine Environmental Research 100: 17–24.

Frantzen, M., Falk-Petersen, I. B., Nahrgang, J., Smith, T. J., Olsen, G. H., Hangstad, T. A., and Camus, L. 2012. Toxicity of crude oil and pyrene to the embryos of beach spawning capelin (*Mallotus villosus*). Aquatic Toxicology 108: 42–52.

Frantzen, S., Maage, A., Duinker, A., Julshamn, K., and Iversen, S. A. 2015. A baseline study of metals in herring (*Clupea harengus*) from the Norwegian Sea, with focus on mercury, cadmium, arsenic and lead. Chemosphere 127: 164–170.

Gilliers, C., Le Pape, O., Désaunay, Y., Morin, J., Guérault, D., and Amara, R. 2006. Are growth and density quantitative indicators of essential fish habitat quality? An application to the common sole *Solea solea* nursery grounds. Estuarine, Coastal and Shelf Science 69: 96–106.

Goodsir, F., Bloomfield, H. J., Judd, A. D., Kral, F., Robinson, L. A., and Knights, A. M. 2015. A spatially resolved pressure-based approach to evaluate combined effects of human activities and management in marine ecosystems. ICES Journal of Marine Science 72: 2245–2256.

Goren, M., and Galil, B. S. 2005. A review of changes in the fish assemblages of Levantine inland and marine ecosystems following the introduction of non-native fishes. Journal of Applied Ichthyology 21: 364–370.

Gorokhova, E., Fagerberg, T., and Hansson, S. 2004. Predation by herring (*Clupea harengus*) and sprat (*Sprattus sprattus*) on *Cercopagis pengoi* in a western Baltic Sea bay. ICES Journal of Marine Science 61: 959–965.

Gorokhova, E., Hansson, S., Höglander, H., and Andersen, C. M. 2005. Stable isotopes show food web changes after invasion by the predatory cladoceran *Cercopagis pengoi* in a Baltic Sea bay. Oecologia 143: 251–259.

Hall-Spencer, J. M., Grall, J., Moore, P. G., and Atkinson, R. J. A. 2003. Bivalve fishing and maerl-bed conservation in France and the UK—retrospect and prospect. Aquatic Conservation: Marine and Freshwater Ecosystems 13: S33.

Halpern, B. S., Ebert, C. M., Kappel, C. V., Madin, E. M. P., Micheli, F., Perry, M., Selkoe, K. A. et al. 2009. Global priority areas for incorporating land–sea connections in marine conservation. Conservation Letters 2: 1–8.

Halpern, B. S., Selkoe, K. A., Micheli, F., and Kappel, C. V. 2007. Evaluating and ranking the vulnerability of global marine ecosystems to anthropogenic threats. Conservation Biology 21: 1301–1315.

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., Bruno, J. F. et al. 2008. A global map of human impact on marine ecosystems. Science 319: 948–952.

Henriques, S., Pais, M. P., Vasconcelos, R. P., Murta, A., Azevedo, M., Costa, M. J., Cabral, H. N. et al. 2014. Structural and functional trends indicate fishing pressure on marine fish assemblages. Journal of Applied Ecology 51: 623–631.

Hiddink, J. G., Jennings, S., Kaiser, M. J., Queirós, A. M., Duplisea, D. E., and Piet, G. J. 2006. Cumulative impacts of seabed trawl disturbance on benthic biomass, production, and species richness in different habitats. Canadian Journal of Fisheries and Aquatic Sciences 63: 721–736.

Holmlund, C. M., and Hammer, M. 1999. Ecosystem services generated by fish populations. Ecological Economics 29: 253–268.

Houlihan, D. F., Costello, M. J., Secombes, C. J., Stagg, R., and Brechin, J. 1994. Effects of sewage sludge exposure on growth, feeding and protein synthesis of dab (*Limanda limanda* (L.)). Marine Environmental Research 37: 331–353.

Ilarri, M. I., Souza, A. T., Antunes, C., Guilhermino, L., and Sousa, R. 2014. Influence of the invasive Asian clam *Corbicula fluminea* (Bivalvia: Corbiculidae) on estuarine epibenthic assemblages. Estuarine, Coastal and Shelf Science 143: 12–19.

Isaksson, I., Pihl, L., and van Montfrans, J. 1994. Eutrophication-related changes in macrovegetation and foraging of young cod (*Gadus morhua* L.): a mesocosm experiment. Journal of Experimental Marine Biology and Ecology 177: 203–217.

Jebali, J., Sabbagh, M., Banni, M., Kamel, N., Ben-Khedher, S., M'hamdi, N., and Boussetta, H. 2013. Multiple biomarkers of pollution effects in *Solea solea* fish on the Tunisia coastline. Environmental Science and Pollution Research 20: 3812–3821.

Jenkinson, I. R., Claireaux, G., and Gentien, P. 2007. Biorheological properties of intertidal organic fluff on mud flats and its modification of gill ventilation in buried sole *Solea solea*. Marine Biology 150: 471–485.

Jennings, S., and Rice, J. 2011. Towards an ecosystem approach to fisheries in Europe: a perspective on existing progress and future directions. Fish and Fisheries 12: 125–137.

Johannessen, T. 2014. Repeated incidents of abrupt and persistent recruitment failures in gadoids in relation to increasing eutrophication, 1919–2001. *In* From an Antagonistic to a Synergistic Predator Prey Perspective, pp. 11–37. Ed. by T. Johannessen. Elsevier, London.

Johansen, J. L., Herbert, N. A., and Steffensen, J. F. 2006. The behavioural and physiological response of Atlantic cod *Gadus morhua* L. to short-term acute hypoxia. Journal of Fish Biology 68: 1918–1924.

Johansen, L., Jensen, I., Mikkelsen, H., Bjørn, P., Jansen, P. A., and Bergh, Ø. 2011. Disease interaction and pathogens exchange between wild and farmed fish populations with special reference to Norway. Aquaculture 315: 167–186.

Johnston, D. W., and Wildish, D. J. 1981. Avoidance of dredge spoil by herring (*Clupea harengus harengus*). Bulletin of Environmental Contamination and Toxicology 26: 307–314.

Jokinen, H., Wennhage, H., Ollus, V., Aro, E., and Norkko, A. 2016. Juvenile flatfish in the northern Baltic Sea—long-term decline and potential links to habitat characteristics. Journal of Sea Research 107: 67–75.

Jonsson, B., and Jonsson, N. 2014. Early environment influences later performance in fishes. Journal of Fish Biology 85: 151–188.

Kamenos, N. A., Moore, P. G., and Hall-Spencer, J. M. 2004. Small-scale distribution of juvenile gadoids in shallow inshore waters; what role does maerl play? ICES Journal of Marine Science 61: 422–429.

Kempf, A. 2010. Ecosystem approach to fisheries in the European context—history and future challenges. Journal of Applied Ichthyology 26: 102–109.

Kerambrun, E., Henry, F., Courcot, L., Gevaert, F., and Amara, R. 2012. Biological responses of caged juvenile sea bass (*Dicentrarchus labrax*) and turbot (*Scophtalmus maximus*) in a polluted harbour. Ecological Indicators 19: 161–171.

Kerambrun, E., Henry, F., Perrichon, P., Courcot, L., Meziane, T., Spilmont, N., and Amara, R. 2012a. Growth and condition indices of juvenile turbot, *Scophthalmus maximus*, exposed to contaminated sediments: effects of metallic and organic compounds. Aquatic Toxicology 108: 130–140.

Kideys, A. 1994. Recent dramatic changes in the Black Sea ecosystem: the reason for the sharp decline in Turkish anchovy fisheries. Journal of Marine Systems 5: 171–181.

Klanjšček, J., and Legović, T. 2007. Is anchovy (*Engraulis encrasicolus*, L.) overfished in the Adriatic Sea? Ecological Modelling 201: 312–316.

Knights, A. M., Piet, G. J., Jongbloed, R. H., Tamis, J. E., White, L., Akoglu, E., Boicenco, L. et al. 2015. An exposure-effect approach for evaluating ecosystem-wide risks from human activities. ICES Journal of Marine Science 72: 1105–1115.

Koons, D. N., Arnold, T. W., and Schaub, M. 2017. Understanding the demographic drivers of realized population growth rates. Ecological Applications 27: 2102–2115.

Kornilovs, G. 1993. The modern state of Baltic herring spawning grounds in the Gulf of Riga. ICES Document CM *1993*/J: 26. 6 pp.

Kostecki, C., Rochette, S., Girardin, R., Blanchard, M., Desroy, N., and Le Pape, O. 2011. Reduction of flatfish habitat as a consequence of the proliferation of an invasive mollusc. Estuarine, Coastal and Shelf Science 92: 154–160.

Kummu, M., de Moel, H., Salvucci, G., Viviroli, D., Ward, P. J., and Varis, O. 2016. Over the hills and further away from coast: global geospatial patterns of human and environment over the 20th–21st centuries. Environmental Research Letters 11: 15..

Laffaille, P., Lefeuvre, J.-C., and Feunteun, E. 2000. Impact of sheep grazing on juvenile sea bass, *Dicentrarchus labrax* L., in tidal salt marshes. Biological Conservation 96: 271–277.

Lagares, E. C., and Ordaz, F. G. 2014. Fisheries structural policy in the European Union: a critical analysis of a subsidised sector. Ocean and Coastal Management 102: 200–211.

Lappalainen, A., and Pesonen, L. 2000. Changes in fish community structure after cessation of waste water discharge in a coastal bay area west of Helsinki, northern Baltic Sea. Archive of Fishery and Marine Research Archiv fur Fischerei und Meeresforschung 48: 226–241@p84keBB&page=1&doc=1.

Lefrançois, C., and Claireaux, G. 2003. Influence of ambient oxygenation and temperature on metabolic scope and scope for heart rate in the common sole *Solea solea*. Marine Ecology Progress Series 259: 273–284.

Le Luherne, E., Réveillac, E., Ponsero, A., Sturbois, A., Ballu, S., Perdriau, M., and Le Pape, O. 2016. Fish community responses to green tides in shallow estuarine and coastal areas. Estuarine, Coastal and Shelf Science 175: 79–92.

Le Pape, O., Baulier, L., Cloarec, A., Martin, J., Le Loc'h, F., and Désaunay, Y. 2007. Habitat suitability for juvenile common sole (*Solea solea*, L.) in the Bay of Biscay (France): a quantitative description using indicators based on epibenthic fauna. Journal of Sea Research 57: 126–136.

Le Pape, O., Guérault, D., and Désaunay, Y. 2004. Effect of an invasive mollusc, American slipper limpet *Crepidula fornicata*, on habitat suitability for juvenile common sole *Solea solea* in the Bay of Biscay. Marine Ecology Progress Series 277: 107–115.

Levi, F., and Francour, P. 2004. Behavioural response of *Mullus surmuletus* to habitat modification by the invasive macroalga *Caulerpa taxifolia*. Journal of Fish Biology 64: 55–64.

Levin, P. S., and Stunz, G. W. 2005. Habitat triage for exploited fishes: can we identify essential 'Essential Fish Habitat?'. Estuarine, Coastal and Shelf Science 64: 70–78.

Lindholm, J. B., Auster, P. J., and Kaufman, L. S. 1999. Habitat-mediated survivorship of juvenile (0-year) Atlantic cod *Gadus morhua*. Marine Ecology Progress Series 180: 247–255.

Longwell, A. C., Chang, S., Hebert, A., Hughes, J. B., and Perry, D. 1992. Pollution and developmental abnormalities of Atlantic fishes. Environmental Biology of Fishes 35: 1–21.

Lotze, H. K., Lenihan, H. S., Bourque, B. J., Bradbury, R. H., Cooke, R. G., Kay, M. C., Kidwell, S. M. et al. 2006. Depletion, degradation, and recovery potential of estuaries and coastal seas. Science 312: 1806–1809.

Lotze, H. K., Reise, K., Worm, B., van Beusekom, J., Busch, M., Ehlers, A., Heinrich, D. et al. 2005. Human transformations of the Wadden Sea ecosystem through time: a synthesis. Helgoland Marine Research 59: 84–95.

Maes, J., Stevens, M., and Breine, J. 2007. Modelling the migration opportunities of diadromous fish species along a gradient of dissolved oxygen concentration in a European tidal watershed. Estuarine, Coastal and Shelf Science 75: 151–162.

Malovic, I., Hemmingsen, W., and MacKenzie, K. 2010. Trypanosome infections of marine fish in the southern Barents Sea and the invasive red king crab *Paralithodes camtschaticus*. Marine Pollution Bulletin 60: 2257–2262.

Martignac, F., Baglinière, J. L., Thieulle, L., Ombredane, D., and Guillard, J. 2013. Influences of a dam on Atlantic salmon (*Salmo salar*) upstream migration in the Couesnon River (Mont Saint Michel Bay) using hydroacoustics. Estuarine, Coastal and Shelf Science 134: 181–187.

McIntosh, S., King, T., Wu, D., and Hodson, P. V. 2010. Toxicity of dispersed weathered crude oil to early life stages of Atlantic herring (*Clupea harengus*). Environmental Toxicology and Chemistry 29: 1160–1167.

Meland, S., Salbu, B., and Rosseland, B. O. 2010. Ecotoxicological impact of highway runoff using brown trout (*Salmo trutta* L.) as an indicator model. Journal of Environmental Monitoring 12: 654–664.

Meynecke, J.-O., and Richards, R. G. 2014. A full life cycle and spatially explicit individual-based model for the giant mud crab (*Scylla serrata*): a case study from a marine protected area. ICES Journal of Marine Science 71: 484–498.

Molnar, J. L., Gamboa, R. L., Revenga, C., and Spalding, M. D. 2008. Assessing the global threat of invasive species to marine biodiversity. Frontiers in Ecology and the Environment 6: 485–492.

Mumby, P. J., Edwards, A. J., Arias-González, J. E., Lindeman, K. C., Blackwell, P. G., Gall, A., Gorczynska, M. I. et al. 2004. Mangroves enhance the biomass of coral reef fish communities in the Caribbean. Nature 427: 533–536.

Niermann, U., Bingel, F., Gorban, A., Gordina, A. D., Gücü, A. C., Kideys, A. E., and Konsulov, A. 1994. Distribution of anchovy eggs and larvae (*Engraulis encrasicolus* Cuv.) in the Black Sea in 1991-1992. ICES Journal of Marine Science 51: 395–406.

Ogut, H., and Palm, H. W. 2005. Seasonal dynamics of *Trichodina* spp. on whiting (*Merlangius merlangus*) in relation to organic pollution on the eastern Black Sea coast of Turkey. Parasitology Research 96: 149–153.

Oguz, T., Fach, B., and Salihoglu, B. 2008. Invasion dynamics of the alien ctenophore *Mnemiopsis leidyi* and its impact on anchovy collapse in the Black Sea. Journal of Plankton Research 30: 1385–1397.

Olsen, E., Aanes, S., Mehl, S., Holst, J. C., Aglen, A., and Gjosaeter, H. 2010. Cod, haddock, saithe, herring, and capelin in the Barents Sea and adjacent waters: a review of the biological value of the area. ICES Journal of Marine Science 67: 87–101.

Olsson, I. C., Greenberg, L. A., and Eklöv, A. G. 2001. Effect of an artificial pond on migrating brown trout smolts. North American Journal of Fisheries Management 21: 498–506.

Österblom, H., Hansson, S., Larsson, U., Hjerne, O., Wulff, F., Elmgren, R., and Folke, C. 2007. Human-induced trophic cascades and ecological regime shifts in the Baltic Sea. Ecosystems 10: 877–889.

Öztürk, B. 2006. Invasive species of the Turkish Straits. *In* The Turkish Straits: Maritime Safety, Legal and Environmental Aspects, pp. 96–105. Ed. by N. Oral, and B. Öztürk. Turkish Marine Research Foundation, İstanbul. Publication Number 25. 160 pp.

Palstra, A. P., Van Ginneken, V. J. T., Murk, A. J., and Van Den Thillart, G. E. E. J. M. 2006. Are dioxin-like contaminants responsible for the eel (*Anguilla anguilla*) drama? Naturwissenschaften 93: 145–148.

Parmanne, R., Rechlin, O., and Sjöstrand, B. 1994. Status and future of herring and sprat stocks in the Baltic Sea. Dana 10: 29–59.

Patel, S., Korsnes, K., Bergh, Ø., Vik-Mo, F., Pedersen, J., and Nerland, A. 2007. Nodavirus in farmed Atlantic cod *Gadus morhua* in Norway. Diseases of Aquatic Organisms 77: 169–173.

Peters, L. D., Porte, C., and Livingstone, D. R. 2001. Variation of antioxidant enzyme activities of sprat (*Sprattus sprattus*) larvae and organic contaminant levels in mixed zooplankton from the southern North Sea. Marine Pollution Bulletin 42: 1087–1095.

Petersen, J. K., and Pihl, L. 1995. Responses to hypoxia of plaice, *Pleuronectes platessa*, and dab, *Limanda limanda*, in the south-east Kattegat: distribution and growth. Environmental Biology of Fishes 43: 311–321.

Peterson, C. H., Bishop, M. J., D'Anna, L. M., and Johnson, G. A. 2014. Multi-year persistence of beach habitat degradation from nourishment using coarse shelly sediments. Science of the Total Environment 487: 481–492.

Piggott, J. J., Townsend, C. R., and Matthaei, C. D. 2015. Reconceptualizing synergism and antagonism among multiple stressors. Ecology and Evolution 5: 1538–1547.

Pihl, L., Modin, J., and Wennhage, H. 2005. Recruitment to deteriorating habitat quality: effects of macroalgal blooms in coastal nursery grounds. Canadian Journal of Fisheries and Aquatic Sciences 62: 1184–1193.

Pihl, L., Baden, S., Kautsky, N., Rönnbäck, P., Söderqvist, T., Troell, M., and Wennhage, H. 2006. Shift in fish assemblage structure due to loss of seagrass *Zostera marina* habitats in Sweden. Estuarine, Coastal and Shelf Science 67: 123–132.

Power, M., Attrill, M. J., and Thomas, R. M. 2000. Environmental factors and interactions affecting the temporal abundance of juvenile flatfish in the Thames Estuary. Journal of Sea Research 43: 135–149.

Rabalais, N. N. 2015. Human impacts on fisheries across the land–sea interface. Proceedings of the National Academy of Sciences 112: 7892–7893.

Rahikainen, M., Hoviniemi, K.-M., Mäntyniemi, S., Vanhatalo, J., Helle, I., Lehtiniemi, M., Pönni, J. et al. 2017. Impacts of eutrophication and oil spills on the Gulf of Finland herring stock. Canadian Journal of Fisheries and Aquatic Sciences 74: 1218–1232.

Reubens, J. T., Braeckman, U., Vanaverbeke, J., Van Colen, C., Degraer, S., and Vincx, M. 2013. Aggregation at windmill artificial reefs: CPUE of Atlantic cod (*Gadus morhua*) and pouting (*Trisopterus luscus*) at different habitats in the Belgian part of the North Sea. Fisheries Research 139: 28–34.

Reynolds, W. J., Lancaster, J. E., and Pawson, M. G. 2003. Patterns of spawning and recruitment of sea bass to Bristol Channel nurseries in relation to the 1996 'Sea Empress' oil spill. Journal of the Marine Biological Association of the UK 83: 1163–1170.

Rijnsdorp, A. D., Bastardie, F., Bolam, S. G., Buhl-Mortensen, L., Eigaard, O. R., Hamon, K. G., Hiddink, J. G. et al. 2016. Towards a framework for the quantitative assessment of trawling impact on the seabed and benthic ecosystem. ICES Journal of Marine Science 73: i127–i138.

Rochette, S., Le Pape, O., Vigneau, J., and Rivot, E. 2013. A hierarchical Bayesian model for embedding larval drift and habitat models in integrated life cycles for exploited fish. Ecological Applications 23: 1659–1676.

Rochette, S., Rivot, E., Morin, J., Mackinson, S., Riou, P., and Le Pape, O. 2010. Effect of nursery habitat degradation on flatfish population: application to *Solea solea* in the Eastern Channel (Western Europe). Journal of Sea Research 64: 34–44.

Ruiz, J., González-Quirós, R., Prieto, L., and Navarro, G. 2009. A Bayesian model for anchovy (*Engraulis encrasicolus*): the combined forcing of man and environment. Fisheries Oceanography 18: 62–76.

Schmidt, B. R., Hödl, W., and Schaub, M. 2012. From metamorphosis to maturity in complex life cycles: equal performance of different juvenile life history pathways. Ecology 93: 657–667.

Sciberras, M., and Hiddink, J. G. 2014. Predicting the effect of trawling based on biological traits of organisms and functional correlates of these traits to predict which functions may be disproportionally affected. Benthic Ecosystem Fisheries Impact Study, IMARES, IJmuiden, The Netherlands, Deliverable 4.3. 125 pp. http://www.benthis.eu/web/file? uuid=ac0db45d-135d-4b84-806d-9a9408bf2b6e&owner=fd9fa22c-6bf7-42dc-ad64-ad4cbd966f98 (Accessed 11 April 2016).

Scopelliti, G., Di Leonardo, R., Tramati, C. D., Mazzola, A., and Vizzini, S. 2015. Premature aging in bone of fish from a highly polluted marine area. Marine Pollution Bulletin 97: 333–341.

Secombes, C. J., White, A., Fletcher, T. C., Stagg, R., and Houlihan, D. F. 1995. Immune parameters of plaice, *Pleuronectes platessa*, L. along a sewage sludge gradient in the Firth of Clyde, Scotland. Ecotoxicology 4: 329–340.

Seitz, R. D., Wennhage, H., Bergström, U., Lipcius, R. N., and Ysebaert, T. 2014. Ecological value of coastal habitats for commercially and ecologically important species. ICES Journal of Marine Science 71: 648–655 (Accessed 1 December 2014).

Shiganova, T. A., and Bulgakova, Y. V. 2000. Effects of gelatinous plankton on Black Sea and Sea of Azov fish and their food resources. ICES Journal of Marine Science 57: 641–648.

Shiganova, T. A., Mirzoyan, Z. A., Studenikin, E. A., Volovik, S. P., Siokou-Frangou, I., Zervoudaki, S., Christou, E. D., Skirta, A. Y., Dumont, H. J. 2001. Population development of the invader ctenophore *Mnemiopsis leidyi*, in the Black Sea and in other seas of the Mediterranean basin. Marine Biology 139: 431–445.

Stelzenmüller, V., Schulze, T., Fock, H. O., and Berkenhagen, J. 2011. Integrated modelling tools to support risk-based decision-making in marine spatial management. Marine Ecology Progress Series 441: 197–212.

Støttrup, J. G., Stenberg, C., Dahl, K., Kristensen, L. D., and Richardson, K. 2014. Restoration of a temperate reef: effects on the fish community. Open Journal of Ecology 04: 4: 1045–1059.

Sundblad, G., Bergström, U., Sandstrom, A., and Eklov, P. 2014. Nursery habitat availability limits adult stock sizes of predatory coastal fish. ICES Journal of Marine Science 71: 672–680.

Taranger, G. L., Karlsen, Ø., Bannister, R. J., Glover, K. A., Husa, V., Karlsbakk, E., Kvamme, B. O. et al. 2015. Risk assessment of the environmental impact of Norwegian Atlantic salmon farming. ICES Journal of Marine Science 72: 997–1021.

Teichert, N., Borja, A., Chust, G., Uriarte, A., and Lepage, M. 2016. Restoring fish ecological quality in estuaries: implication of interactive and cumulative effects among anthropogenic stressors. Science of the Total Environment 542: 383–393.

Tentelier, C., and Piou, C. 2011. Obstacles to migration constrain nest distribution of Atlantic salmon. Ecology of Freshwater Fish 20: 400–408.

Teschner, E. C., Kraus, G., Neuenfeldt, S., Voss, R., Hinrichsen, H. H., and Köster, F. W. 2010. Impact of hypoxia on consumption of Baltic cod in a multispecies stock assessment context. Journal of Applied Ichthyology 26: 836–842.

Thurstan, R. H., Roberts, C. M., and Unsworth, R. K. F. 2010. Ecological meltdown in the Firth of Clyde, Scotland: two centuries of change in a coastal marine ecosystem. PLoS One 5: e11767.

Tomczak, M. T., Heymans, J. J., Yletyinen, J., Niiranen, S., Otto, S. A., Blenckner, T., and MacKenzie, B. R. 2013. Ecological network indicators of ecosystem status and change in the Baltic Sea. PLoS ONE 8: 1–11.

Tsikhon-Lykanina, E. A., and Reznitchenko, O. G. 1991. Feeding peculiarities of different size species of ctenophore *Mnemiopsis* in the Black Sea. Oceanology 31: 442–446.

Turnpenny, A. W., and Taylor, C. J. 2000. An assessment of the effect of the Sizewell power stations on fish populations. Hydroécologie Appliquée 12: 87–134.

van Denderen, P. D., Hintzen, N. T., Rijnsdorp, A. D., Ruardij, P., and van Kooten, T. 2014. Habitat-specific effects of fishing disturbance on benthic species richness in marine soft sediments. Ecosystems 17: 1216–1226.

van de Wolfshaar, K. E., HilleRisLambers, R., and Gårdmark, A. 2011. Effect of habitat productivity and exploitation on populations with complex life cycles. Marine Ecology Progress Series 438: 175–184.

Vasconcelos, R. P., Batista, M. I., and Henriques, S. 2017. Current limitations of global conservation to protect higher vulnerability and lower resilience fish species. Scientific Reports 7: 7702..

Vasconcelos, R. P., Reis-Santos, P., Fonseca, V., Maia, A., Ruano, M., França, S., Vinagre, C.et al. 2007. Assessing anthropogenic pressures on estuarine fish nurseries along the Portuguese coast: a multi-metric index and conceptual approach. Science of the Total Environment 374: 199–215.

Via, J. D., Van den Thillart, G., Cattani, O., and Cortesi, P. 1998. Behavioural responses and biochemical correlates in *Solea solea* to gradual hypoxic exposure. Canadian Journal of Zoology 76: 2108–2113.

Westernhagen, H., Cameron, P., Dethlefsen, V., and Janssen, D. 1989. Chlorinated hydrocarbons in North Sea whiting (*Merlangius merlangus* L), and effects on reproduction. I. Tissue burden and hatching success. Helgoländer Meeresuntersuchungen 43: 45–60.

Winters, G. H., Wheeler, J. P., and Dalley, E. L. 1986. Survival of a herring stock subjected to a catastrophic event and fluctuating environmental conditions. Journal du Conseil International pour l'Exploration de la Mer 43: 26–42.

Worm, B., Barbier, E. B., Beaumont, N., Duffy, J. E., Folke, C., Halpern, B. S., Jackson, J. B. C. et al. 2006. Impacts of biodiversity loss on ocean ecosystem services. Science 314: 787–790.

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